

A new substantive proton to electron mass ratio constraint on rolling scalar field cosmologies

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ABSTRACT

New PKS1830-211 radio frequency observations of methanol at a redshift of 0.88582 have established the most stringent limits on changes in the proton to electron mass ratio μ to date. The observations place the limit of $\delta\mu/\mu \leq (0.0 \pm 1.0) \times 10^{-7}$ which is approximately a factor of four lower than the previous lowest limit at a redshift of 0.6742. This stringent limit at a look back time of roughly half the age of the universe has profound implications for rolling scalar field cosmologies and the new physics that they require. Many of these cosmologies invoke a scalar field ϕ that is also coupled to the electromagnetic field causing the values of the fundamental constants, μ and the fine structure constant α to roll with time. If the lowest expected value of the coupling to μ , ζ_μ , is invoked the new limit requires a limit on the dark energy equation of state parameter w such that $(w+1) \leq 0.001$ at a redshift of 0.88582. This eliminates almost all of the expected parameter space for such cosmologies and new physics **that have a coupling to the electromagnetic field. In these cases** the limit requires that w must be extremely close to -1 for the last half of the age of the universe or that the coupling of the rolling scalar field to μ and the electromagnetic field be significantly below or at the limit of its expected range. The new observations solidify the role of fundamental constants in providing probes of the possible cosmologies and new physics to explain the acceleration of the expansion of the universe.

Key words: (cosmology:) cosmological parameters – dark energy – theory – early universe .

1 INTRODUCTION

Tracking the values of the fundamental constants such as the proton to electron mass ratio μ and the fine structure constant α has been shown to be an effective way of discriminating between different mechanisms for the acceleration of the expansion of the universe (Thompson (2012), Thompson, Martins & Vielzeuf (2013), hereinafter T12 and TMV13). In particular rolling scalar field cosmologies where the rolling field also couples with the electromagnetic field predict changes in the values of μ and α . Comparison of the predicted changes in μ with the observed constraints translates to equivalent constraints on the cosmologies and the new physics required by the cosmology.

A new constraint on the change in μ at a redshift of 0.89 has just been published by Bagdonaite, Jansen, Henkel, Bethlehem, Menten & Ubachs (2012). They find $\Delta\mu/\mu = (0.0 \pm 1.0) \times 10^{-7}$ in the radio

absorption spectrum of PKS 1830-211 at a redshift of 0.88582. This more than a factor of six improvement over the previous limit of $\Delta\mu/\mu = (0.0 \pm 6.3) \times 10^{-7}$ in the same object (Ellingsen, Voronkov, Breen & Lovell 2012) and almost a factor of 4 improvement over the previous lower limit at a redshift of 0.6847 (Kanekar 2011). The 3σ constraint is based on 4 methanol absorption lines observed with the 100m Effelsberg radio telescope. Two of the absorption lines are normal rotational transitions while the two other transitions are mixed torsion-rotation transitions. The sensitivity constant K_μ , defined by $\Delta\nu/\nu = K_\mu \times \Delta\mu/\mu$ for the two pure rotational transitions is -1 while the two torsion-rotation transitions have sensitivity constants of -7.4 and -32.8. The differences in sensitivity constants provides a means of testing for a change in μ using transitions in a single molecular species rather than comparison between two or more molecular species.

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2 CONSTRAINTS ON ROLLING SCALAR FIELD COSMOLOGIES

The connection between rolling scalar fields and changes in the values of the fundamental constants has been considered for more than 10 years, eg. Chiba & Kohri (2002) and Dvali & Zaldarriaga (2002). It is assumed in most rolling scalar field cosmologies that the rolling scalar field ϕ is also coupled with the electromagnetic field (Copeland et al. 2004). This coupling then alters the values of the fundamental constants as the field changes with time (rolls). This has been discussed by Nunes & Lidsey (2004), hereinafter NL4 in the context of a linear coupling

$$\frac{\Delta x}{x} = \zeta_x \kappa (\phi - \phi_0) \quad (1)$$

where $x = \mu, \alpha$, ζ is the coupling constant and $\kappa = \frac{\sqrt{8\pi}}{m_p}$ where m_p is the Planck mass. The same physics applies to both μ and α and the two are related by

$$\frac{\dot{\mu}}{\mu} \sim \frac{\dot{\Lambda}_{QCD}}{\Lambda_{QCD}} - \frac{\dot{\nu}}{\nu} \sim R \frac{\dot{\alpha}}{\alpha} \quad (2)$$

where Λ_{QCD} is the QCD scale, ν is the Higgs vacuum expectation value and R is a scalar often considered to be on the order of -40 to -50 (Avelino et al. 2006). NL4 further show the relationship between the rolling field and the equation of state parameter $w \equiv \frac{p_\phi}{\rho_\phi} = \frac{\dot{\phi}^2 - 2V(\phi)}{\dot{\phi}^2 + 2V(\phi)}$ as

$$w + 1 = \frac{(\kappa\phi')^2}{3\Omega_\phi} \quad (3)$$

where Ω_ϕ is the dark energy density. Here $\dot{\phi}$ and ϕ' indicate differentiation with respect to cosmic time and to $N = \log a$ respectively where a is the scale factor of the universe. T12 and TMV13 then showed the relation between changing fundamental constants and the evolution of w .

$$(w + 1) = \frac{(\mu'/\mu)^2}{3\zeta_\mu^2 \Omega_\phi} = \frac{(\alpha'/\alpha)^2}{3\zeta_\alpha^2 \Omega_\phi} \quad (4)$$

For the case of the proton to electron mass ratio Equation 4 establishes the connection between the product of a new physics parameter ζ_μ^2 and a cosmological parameter $(w + 1)$ such that

$$(w + 1)\zeta_\mu^2 = \frac{(\mu'/\mu)^2}{3\Omega_\phi} = \frac{(\Delta\mu/\mu)^2}{3z^2\Omega_\phi} \quad (5)$$

where z is the redshift. **In creating Figures 2 and 3 equation 6 for the dark energy density is used. In section 4 dark energy densities are calculated using equations specific to the particular cosmology.**

$$\Omega_\phi(a) = [1 + (\Omega_{\phi 0}^{-1} - 1)a^{-3}]^{-1} \quad (6)$$

The observational limits on $\Delta\mu/\mu$ therefore impose limits on the $(\Delta\mu/\mu)^2 - (w + 1)$ parameter space that a rolling scalar field cosmology can live in. This parameter space was first discussed in T12, however, the new methanol observation has greatly reduced the available parameter space.

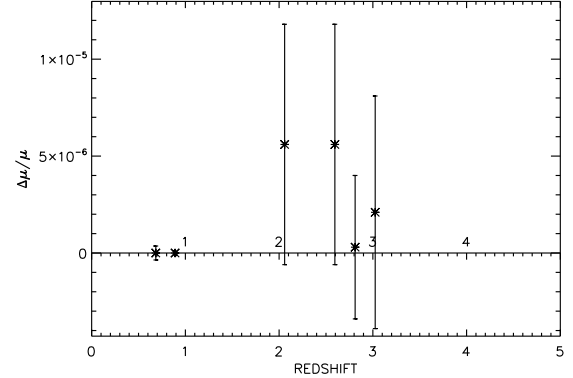


Figure 1. The observed values of $\Delta\mu/\mu$ and their associated errors. Note that the two lowest redshift (radio) errors are 3σ errors while the rest (optical) are 1σ error bars.

3 THE NEW METHANOL CONSTRAINED PARAMETER SPACE

Figure 1 shows the existing constraints on $\Delta\mu/\mu$ where the most stringent constraint for each object is indicated. The radio results are 3σ constraints while the optical constraints are 1σ measurements. All of the measurements are from the references in Table 1 of T12 except for the new PKS 1830-211 measurement by Bagdonaite, Jansen, Henkel, Bethlehem, Menten & Ubachs (2012). It is obvious from Fig. 1 that the current radio results are the most restrictive in terms of $\Delta\mu/\mu$ and provide a condition at $z = 0.88582$ that must be satisfied by any cosmology.

Figure 2 shows the effect of the new measurement on the $(\Delta\mu/\mu)^2 - (w + 1)$ parameter space along with the other radio restriction at $z = 0.6847$ (Kanekar 2011) and the most restrictive optical measurement at $z = 2.811$ (King et al. 2011). The parameter space diagram in Fig. 2 is similar to the equivalent diagram in T12 with different constraints. The shaded areas indicates the parts of the diagram that are forbidden. All of the area above the bottom line are forbidden at the redshift listed just above the line. All of the light shaded area and above is forbidden by the constraint on $\Delta\mu/\mu$ at $z = 2.88$ and all of the shaded areas and above are forbidden by the new $\Delta\mu/\mu$ measurement at $z = 0.89$.

The dashed line in Fig. 2 indicates the expected lower limit on ζ_μ from new physics. Nunes & Lidsey (2004) use the work of Copeland et al. (2004) to set limits on the expected value of the coupling with the fine structure constant ζ_α of $10^{-7} \leq \zeta_\alpha \leq 10^{-4}$. With the expected value of -40 for R in Eq. 2 this produces the expected range for $|\zeta_\mu|$ of $4 \times 10^{-6} \leq \zeta_\mu \leq 4 \times 10^{-3}$. The lower bound from Nunes & Lidsey (2004) was

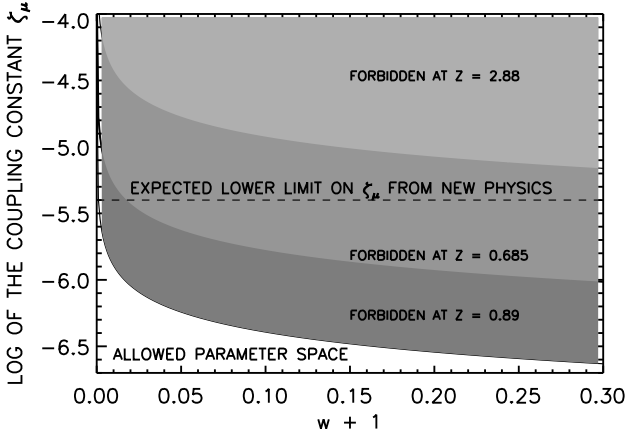


Figure 2. The figure shows the forbidden and allowed parameter space in the ζ_μ , $(w+1)$ plane based on the three most restrictive low and high redshift observations. The upper light shaded area is for the constraint at a redshift of 2.811, the middle darker area and above are for a redshift of 0.685, and lower dark shaded area and above is for the new constraint at a redshift of 0.89. The dashed line indicates the lower expected limit on the coupling factor ζ_μ as discussed in the text.

determined by setting $\Delta\alpha/\alpha = 10^{-7}$, about a factor of 100 below the reported value of $\sim 10^{-5}$ by King et al. (2012).

It is always possible to accommodate any value of $(w+1)$ by lowering the value of ζ_μ , and of course the standard model of physics expects ζ_μ to be zero. This, however, is a test of non-standard models with rolling scalar fields that do interact with the electromagnetic field. It is obvious from Fig. 2 that if we set ζ_μ at its lowest expected value of 4×10^{-6} then, at a redshift of 0.89, the value of w is very close to -1 . Since the value of $\Delta\mu$ is the difference between the value of μ today and its value at $z = 0.89$ this implies that w has been very close to -1 for the entire time between now and $z = 0.89$ unless the scalar field deviates from its value at $z = 0.89$ and then returns to that value at the present time. Most rolling scalar field models do not exhibit this behavior so they must conform to having w close to -1 for roughly half the age of the universe.

To better quantify the restriction Fig 3 shows an expanded view of the region near $(w+1) = 0$. Figure 3 indicates that if we hold to the lowest expected value of ζ_μ we must place the limit of $(w+1) \leq 0.001$ for all redshifts of 0.89 or less. This is an extreme restriction that puts the validity of current models of rolling scalar fields **that also couple with the electromagnetic field** as the driving force for the acceleration of the expansion of the universe in doubt. The results are, however, consistent with a Λ CDM universe and the standard model of physics. Some areas for possible modification of the current rolling scalar field models are discussed in Section 5.

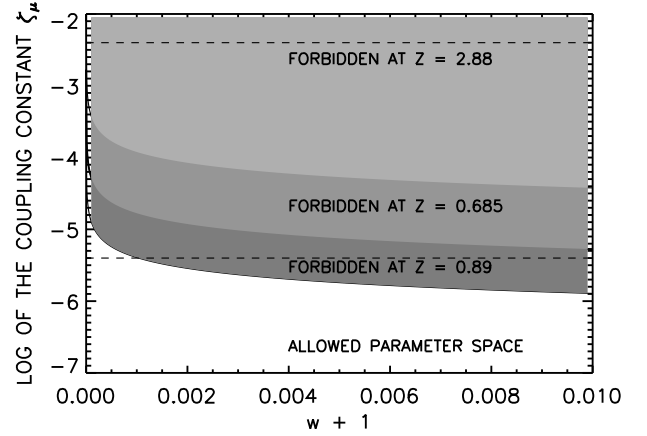


Figure 3. The figure gives a detailed view of the narrow allowed limits on $w+1$ if the value of ζ_μ is taken at its lower expected limit shown by the lower dashed line. At a redshift of 0.89 $w+1$ is constrained to be less than 0.001 unless the coupling constant is reduced below its lowest expected value.

4 EXAMPLES FOR INDIVIDUAL SAMPLE ROLLING SCALAR FIELDS

The $\Delta\mu/\mu$ constraints at the various redshifts provide parameter space "wickets" through which valid cosmologies must pass. Since all of the current "wickets" include the space where $\Delta\mu/\mu = 0$, Λ CDM with the standard model of physics clears all of them as do most modified gravity theories. Rolling scalar field models with non-standard physics do not necessarily pass the test. TMV13 investigated some quintessence and K-Essence models to determine the parameter space that fit the observations, where in this case the parameter space included those individual parameters that define the particular model such as an initial value of w at a given value of redshift. In the following the models examined in TMV13 are used with the new restriction and the same individual model parameters with only ζ_μ being varied to achieve a fit. As described in TMV13 the value of $\Delta\mu/\mu$ at any scale factor a is given by

$$\frac{\Delta\mu}{\mu} = \zeta_\mu \int_1^a \sqrt{3\Omega_\phi(x)(w(x)+1)} x^{-1} dx \quad (7)$$

with $\Omega_\phi(x)$ and $(w(x)+1)$ determined by the details of the particular cosmology. Table 2 of TMV13 lists the values of the parameters used in each of the cosmologies. Note that the matches will be slightly different in the individual cases than in the general case discussed above since in the general case we use Equation 6 for $\Omega_\phi(x)$ whereas in the individual cases we use the more accurate

$$\Omega_\phi(a) = [1 + (\Omega_{\phi 0}^{-1} - 1)a^{-3} \exp(3 \int_1^a \frac{(1+w(x))}{3} dx)]^{-1} \quad (8)$$

Figure 5 from TMV13 plots the values of $w+1$ versus redshift for the 4 cosmologies, slow roll quintessence, hilltop quintessence, non-minimal quintessence, and k-essence, and is repeated here as Fig. 4 for ease of reference. It is obvious from Fig. 4 that none of the three thawing cosmologies come close to satisfying the limit of $(w+1) \leq 0.001$ at a redshift of 0.89. Although not obvious from the scale of the plot even

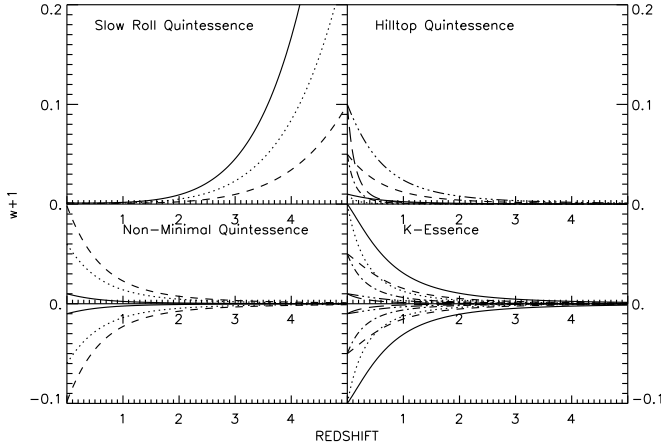


Figure 4. The figure shows the evolution of the equation of state parameter w by plotting the value of $w+1$ as a function of redshift for each of the four cosmologies. The last column of Table 2 in T12 contains the line style code for each of the cases.

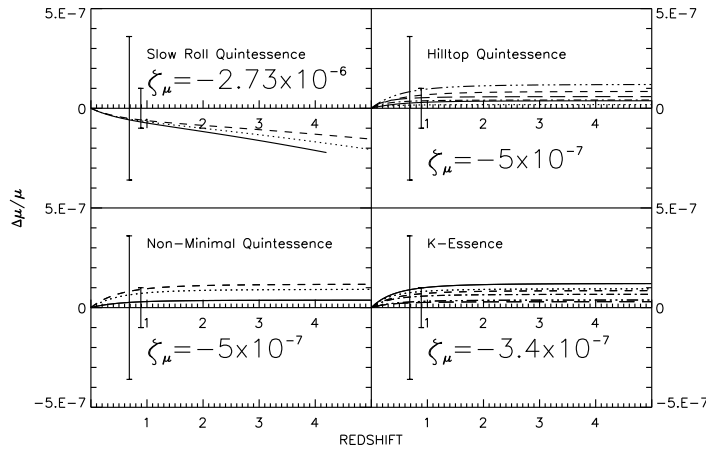


Figure 5. This figure plots the evolution of $\Delta\mu/\mu$ versus redshift for each of the four cosmologies. The value of ζ_μ has been adjusted in each cosmology so that all cases for that cosmology fall within the observational constraints. The higher redshift constraint at $z=2.811$ is not plotted since it is larger than the plot size. The required value of ζ_μ to meet the constraint is printed in each plot. Refer to Table 2 of T12 for the line style for each case.

the freezing slow roll quintessence cosmology does not satisfy the constraint. Since the constraints are in a parameter space that has both a cosmology and a new physics component, solutions can be sought in either area. The easiest is to simply adjust the new physics parameter ζ_μ downward, lower than the expected value, to open up the $w+1$ parameter space. The results of doing this are presented in Fig. 5. The required value of ζ_μ needed to make all of the cases fit the constraints is shown in each figure. In some cases, such as K-Essence the required value of ζ_μ is more than a factor of 10 below the expected lower limit.

5 AREAS FOR THE RECOVERY OF VIABLE ROLLING SCALAR FIELD MODELS

Quantitative and definitive new models for rolling scalar fields are beyond the scope of this paper and will be reserved for future papers. There are, however, obvious areas for modification which are discussed briefly below.

5.1 Varying ζ_μ and or R

The lower bound on ζ_μ as discussed in Section 3 is relatively arbitrary, therefore, the most straightforward method to recover viable rolling scalar field models is to simply reduce the value of ζ_μ by a factor on the order of 10. This recovers most of the $(w+1)$ parameter space appropriate for reasonable cosmological models. This can be accomplished by either making the two terms in equation 2 roughly equal to each other or by lowering the time variation of each of the terms. The former is equivalent to reducing the value of R while the latter reduces all of the coupling between the rolling scalar field and the electromagnetic field. Further discussion of this point is beyond the scope of the present paper.

5.2 The Form of the Coupling to the Electromagnetic Field

Nunes & Lidsey (2004) use a simple linear form of coupling between the electromagnetic field and the scalar field (Equation 1). This is quite reasonable given the lack of information on the true form of the coupling and can be considered as the first term in a Taylor series expansion of the actual coupling. The coupling, however, may be of a quite different form which could lower the effect on the electromagnetic field from the expected range. The coupling has also been considered to be constant with time which may also be an erroneous assumption.

6 SUMMARY

The new limit on $\Delta\mu/\mu$ of $(0.0 \pm 1.0) \times 10^{-7}$ by Bagdonaitė, Jansen, Henkel, Bethlehem, Menten & Ubachs (2012) places significant constraints on rolling scalar fields as the origin of the acceleration of the expansion of the universe. The measured invariance of μ should be considered in the formulation of cosmologies invoking rolling scalar fields. Current results are consistent with acceleration due to a cosmological constant Λ and the standard model of physics. If the expected limits on the coupling constant ζ_μ are accepted then the invariance at a redshift of 0.89 implies that the value of the equation of state variable w has been within 0.001 of -1 for the last half of the age of the universe. **If, however, the coupling between the rolling scalar field and the electromagnetic field is weaker than expected then the constraints on w are significantly relaxed. This, on the other hand, has implications for new physics.** More accurate measurements of μ at higher redshift will be very useful in the further consideration of rolling scalar fields as the

origin of the late time acceleration of the expansion of the universe.

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